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Feedback Effects in the Formation of High Mass and Low Mass Star Formation

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Abstract. The formation of massive stars remains one of the most significant unsolved problems in astrophysics, with implications for the formation of the elements and the structure and evolution of galaxies. It is these stars, with masses greater than 8-10 solar masses, that eventually explode as supernovae and produce most of the heavy elements in the universe, dominate the energy injection into the interstellar medium of galaxies and by injecting both heavy elements and energy into the surrounding medium, shape the evolution of galaxies. Despite the importance of massive star formation, relatively little is known about them theoretically as they pose a major theoretical challenge: How is it possible to sustain a sufficiently high mass accretion rate into a protostellar core despite the radiation pressure on the accreting envelope? I discuss our work on the first 3D simulations of massive star formation. Using our high resolution 3D radiation-hydrodynamic adaptive mesh refinement code ORION with a v/c correct treatment of the radiation transport, we have investigated the formation of high mass stars from both smooth and turbulent initial conditions in the collapsing massive core. I discuss our work on identifying 2 new mechanisms that efficiently solve the problem of the Eddington barrier to high mass star formation; the presence of 3D Rayleigh Taylor instabilities in radiation driven bubbles present in the accreting envelope and the feedback due to protostellar outflows providing radiation an escape mechanism from the accreting envelope in addition to the feedback from protostellar radiation and its affect on stellar multiplicity. I also discuss the effects of radiative transfer on low mass star formation in a turbulent molecular cloud. I compare the distribution of stellar masses, accretion rates, and temperatures in the cases with and without radiative transfer, and demonstrate that radiative feedback has profound effect on accretion, multiplicity, and mass by reducing the number of stars formed and the total rate at which gas turns into stars. Calculations that omit radiative feedback from protostars significantly underestimate the gas temperature and the strength of this effect.

1. Introduction

Massive stars dominate the energy injection in to the interstellar medium (ISM) of galaxies through supernovae, stellar winds and UV radiation. These effects destroy the embryonic clouds and when massive stars are combined, blow vast superbubbles into the ISM. By injecting both heavy elements and energy into the surrounding medium, massive stars shape the evolution of galaxies. Many low–mass stars are born in clusters containing massive stars and HST observations show circumstellar disks around such stars are subject to destruction and photoevaporation (O'Dell 1998). Massive stars lie at the center of the web of physical processes that has shaped the known universe. Feedback from high mass protostars in the formation stage, including radiation heating, radiation presssure, ionization and strong protostellar winds, affect the protostellar disks surrounding the protostars as well as the embryonic cores within which they are born. These feedback affects play a dominant role in the subsequent evolution of the protostar itself. Forming low stars also emit a substantial amount of radiation into their natal environment as well. Radiative feedback can have a profound effect on accretion, multiplicity, and mass of low mass stars.

Several theoretical challenges present themselves in high mass star formation. For massive stars, the Kelvin time is shorter than the formation time (Shu, Adams & Lizano 1987). Consequently, these stars begin to burn their nuclear fuel and radiate enormous amoiunts of energy while they are still the gas accretion phase. For the most massive stars ($M \geq 100 M_{\odot}$), the luminosity can approach the Eddington limit at which the radiative acceleration due to Compton scattering is equal to the acceleration due to gravity. However, the opacity of the accreting matter due to photoionization and to absorption of radiation by dust, can be several orders of magnitude greater than the Thomson cross section. As a result, acceretion due to radiation pressure can greatly exceed that of gravity for stars above $\approx 10 M_{\odot}$. This leads to the first fundamental challenge: How is it possible to sustain a sufficently high–mass accretion rate onto the protostellar core despite the radiation pressure on the accreting envelope (Larson & Starrfield 1971; Kahn 1974; Yorke & Kruegel 1977; Jijina & Adams 1996)? A second fundamental problem facing the theory of high–mass star formation is the presence of powerful protostellar outlfows inferred from observations. Massive young stellar objects have been observed with momentum fluxes up to 100 times greater (Lada 1985; Cesaroni 2004) than fully formed massive stars whose radiation pressure driven momentum fluxes $\dot{M}v \leq L/c$. If these outflows were spherical, this would provide an even greater barrier to accretion than that posed by radiation pressure. The problem is somewhat mitigated however since angular resoluion studies show the outflows tend to be well–collimated (Beuther et al. 2002). Nevertheless, it is crucial to include the effects of outflows in any realistic model of high–mass star formation. How do outflows effect the formation of Massive stars? Do outflows limit the mass of a star?

In this brief paper, I will summarize highlights of our work on the first 3D simulations of massive star formation using our high resolution 3D radiation-hydrodynamic adaptive mesh refinement code ORION (Klein, 1999), as well as our recent work on the feedback effects of radiative transfer on low mass star formation.

2. Physical processes in Massive Star Formation

The problem of high mass star formation is complicated by the several physical processes that are at play and may be critically important in determining the final stellar mass of the star. Strong radiative forces communicated to the dusty accretion envelope surrounding the central protostar oppose the force of gravity of the accreting gas as it attempts to make it way onto the accretion disk surrounding the protostar and make its final plunge onto the star as it builds in mass. A delicate balance between these opposing forces results in a tug of war.

To further complicate the fate of the final mass of the star, strong protostellar outflows and ionizing radiation from the central object also contribute to the balance. See Klein 2008 for a detailed discussion of the physical processes.

3. The Equations of Self–Gravitational Radiation Hydrodynamics

We briefly review the mixed frame equations of radiation-hydrodynamics including self gravity in ORION. For a more complete discussion see Krumholz, Klein & McKee 2007c and Klein & Stone 2008.

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0 &(1)\\
\frac{\partial}{\partial t}(\rho \mathbf{v}) &= -\nabla \cdot (\rho \mathbf{v}\mathbf{v}) - \nabla P - \rho \nabla \phi - \lambda \nabla E &(2)\\
\frac{\partial}{\partial t}(\rho e) &= \rho \mathbf{v} \cdot \nabla \phi - \nabla \cdot [(\rho e + P)\mathbf{v}] - \kappa_{0\mathrm{P}}(4\pi B - cE)\\
&\quad + \lambda \left(2\frac{\kappa_{0\mathrm{P}}}{\kappa_{0\mathrm{R}}} - 1\right) \mathbf{v} \cdot \nabla E\\
&\quad - \frac{3 - R_2}{2} \kappa_{0\mathrm{P}} \frac{v^2}{c} E &(3)\\
\frac{\partial}{\partial t} E &= \nabla \cdot \left(\frac{c\lambda}{\kappa_{0\mathrm{R}}} \nabla E\right) + \kappa_{0\mathrm{P}}(4\pi B - cE)\\
&\quad - \lambda \left(2\frac{\kappa_{0\mathrm{P}}}{\kappa_{0\mathrm{R}}} - 1\right) \mathbf{v} \cdot \nabla E\\
&\quad + \frac{3 - R_2}{2} \kappa_{0\mathrm{P}} \frac{v^2}{c} E\\
&\quad - \nabla \cdot \left(\frac{3 - R_2}{2} \mathbf{v} E\right) &(4)\\
\nabla^2 \phi &= 4\pi G \rho. &(5)
\end{aligned}
$$

These represent the equations of mass conservation, momentum conservation for the gas, energy conservation for the gas, energy conservation for the radiation field and Poisson's equation for the gravitational potential ϕ, which fully describe the system under the approximations we have adopted. The equations are solved in the mixed frame (Mihalas and Klein 1982) in which the absorptivity and opacity are solved in the comoving frame of the fluid and are thus isotropic, and the radiation and fluid field quantities are solved in the observers inertial frame. The mixed frame presents substantial advantages over the comoving frame (Krumholz, Klein & McKee 2007c) They are accurate and consistent to leading order in the streaming and dynamic diffusion limits. They are accurate to first order in β in the static diffusion limit, since we have had to retain all order β terms in this limit because they are of leading order in dynamic diffusion problems. Also note that if in a given problem one never encounters the dynamic diffusion regime, it is possible to drop more terms.

The equations are easy to understand intuitively. The term $-\lambda \nabla E$ in the momentum equation (2) simply represents the radiation force $\kappa_{0\mathrm{R}}\mathbf{F}/c$, neglecting distinctions between the comoving and laboratory frames which are smaller than leading order in this equation and the term $\rho\nabla\phi$ represents the force due to gravity. Similarly, the terms $\pm\kappa_{0\mathrm{P}}(4\pi B - cE)$ and $\pm\lambda(2\kappa_{0\mathrm{P}}/\kappa_{0\mathrm{R}} - 1)\mathbf{v}\cdot\nabla E$ in the two energy equations (3) and (4) represent radiation absorbed minus radiation emitted by the gas, and the work done by the radiation field as it diffuses through the gas. The term R_2 is related to R in Levermore & Pomraning (1981). The factor $(2\kappa_{0\mathrm{P}}/\kappa_{0\mathrm{R}}-1)$ arises because the term contains contributions both from the Newtonian work and from a relativistically-induced mismatch between emission and absorption. The term proportional to $\kappa_{0\mathrm{P}}E/c$ represents another relativistic correction to the work, this one arising from boosting of the flux between the lab and comoving frames. In the radiation energy equation (4), the first term on the left hand side is the divergence of the radiation flux, i.e. the rate at which radiation diffuses, and the last term on the right hand side represents advection of the radiation enthalpy $E+\mathcal{P}$ by the gas. For the static diffusion regime, relevant to massive star formation, further simplifications to these equations can be made (e.g. Krumholz, Klein & McKee 2007c; Klein & Stone 2008).

4. High Mass Star Formation Simulation Physics:ORION-AMR

The state-of-the art in the simulation of massive star formation is the recent work of Krumholz, Klein & McKee (2005, 2007a,b,c). To solve the highly coupled non–linear PDE's represented by equations 1–5, these authors have developed the 3D, parallel AMR code ORION which solves the Euler equations of compressible gas dynamics with self-gravity on an AMR mesh with a high–order Godunov scheme for the hydrodynamics and multi–grid solvers for the self gravity. The radiative transfer is treated in the flux–limited diffusion (FLD) approximation in both grey and multi-frequency, and this provides the radiative feedback from the newly formed protostar into the accreting envelope. The radiative transfer includes all important v/c terms and is solved implicitly with a parallel multi–grid iteration scheme that takes into account the coupling of all grids in the AMR framework at a single refinement level as well as coupling across multiple refinement levels. Models of dust opacity include 6 species of dust. Outflows from the protostar are treated with an approximate hydromagnetic outflow model and this provides the dynamical feedback into the acretion envelope. The simulations implement the first treatment of Lagrangian sink particles embedded in an Eulerian grid (Krumholz, McKee & Klein 2004) that are free to move through the grid and continue to accrete gas. The sink particles feed radiation and protostellar outflows back into the grid based upon a protostellar model. The model includes Kelvin Helmholtz contraction, Deuterium and Hydrogen burning and outflows. The combination of AMR with Eulerian based sink particles allows the simulations to span an enormous range of spatial scales.

5. Feedback Effects in High Mass Star Formation

Current simulations of the formation of massive stars are highly complex requiring the accurate numerical solution of several coupled physical processes (see above) that occur over several orders of magnitude of spatial scale. In series of recent papers, Krumholz, Klein & McKee (2005, 2007a,b,c) have made the first 3D simulations incorporating the relevant physical processes to follow the formation of a massive star from the collapse of its embryonic turbulent core down to the formation of the massive protostar. This work has led to solutions to three longstanding problems in massive star formation theory: fragmentation, angular momentum transport, and radiation pressure. Avoiding fragmentation allows gravitational collapse to produce an object ~ 100 times larger than the characteristic mass of gravitational fragmentation (the Jeans mass), which is $\leq 1\ M_{\odot}$ in molecular clouds. Even if collapse could produce such an object, how could the angular momentum in the gas be transported away from the star rapidly enough to allow accretion? Finally, since stars larger than $\sim 20\ M_{\odot}$ produce so much radiation that it exerts a force stronger than the star's gravity, why would stars ever accrete past this mass, as they are observed to?

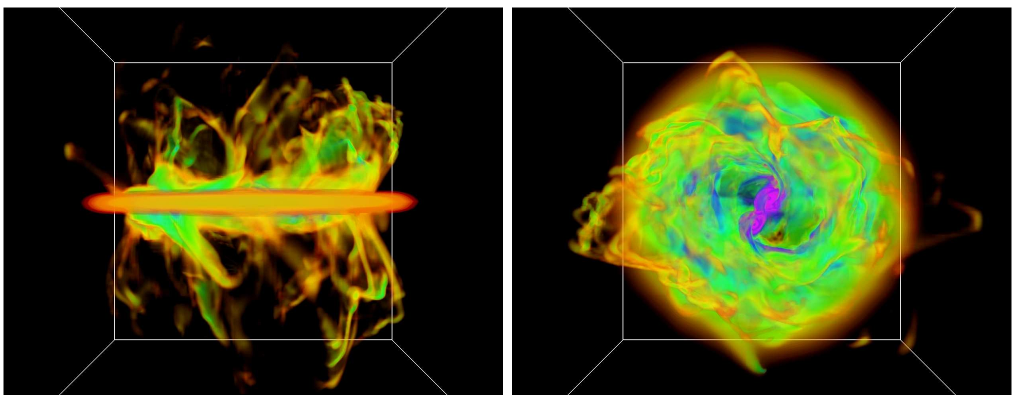

Figure 1. Volume renderings of the density structure in a $(4000\ \mathrm{AU})^3$ region around an accreting 71.7 $M_{\odot}$ binary star system, shown with the disk edge-on (*left*) and face-on (*right*). The Rayleigh-Taylor fingers of accreting gas are clearly visible. Taken from Krumholz et al. (2009).

The problems have been resolved with a series of 3D radiation-hydrodynamic simulations, using our new radiation-hydrodynamics method (Krumholz, Klein, & McKee 2007c). We showed that the radiation emitted by a accreting low-mass stars can heat up clouds to the point where fragmentation is suppressed (Krumholz 2006; Krumholz, Klein, & McKee 2007a), that angular momentum can be transported very rapidly by large-scale gravitational instabilities in the accretion disks around massive stars (which should be observable, as shown in Krumholz, Klein, & McKee 2007b), and that radiation pressure does not halt accretion, because radiation-hydrodynamic instabilities, essentially radiation driven Rayleigh Taylor instabilities, reshape the stellar radiation field, beaming it away from the bulk of the incoming gas (Krumholz et al. 2009). Figure 1 displays a volume rendering showing the instability at work. These simulations also demonstrated convincingly that the disks around massive stars inevitably fragment to produce massive companions, explaining the observed ubiquity of multiple systems among massive stars (e.g. Sana et al. 2008; Gies 2008). This phenomenon had been predicted analytically (Kratter & Matzner

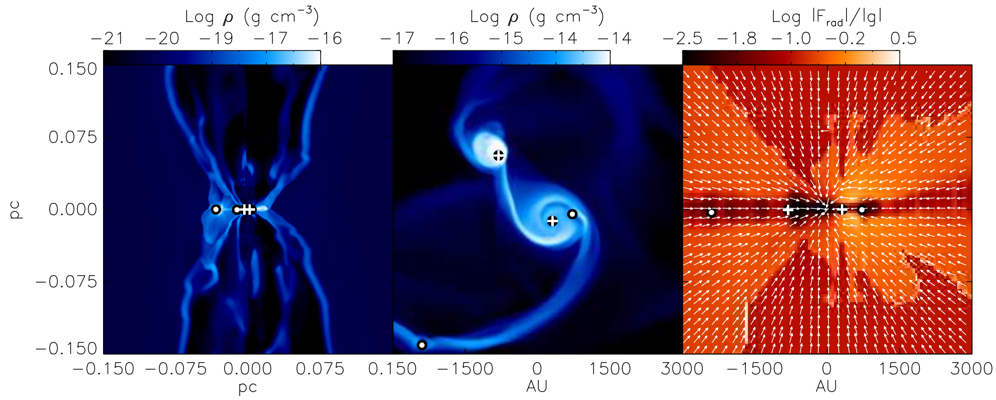

Figure 2. Three dimensional high-mass star formation model with outflows showing cross cuts of the gas density about the outflow and disk symmetry planes in the left and center panels respectively, the ratio of the radiation to gravitational force with arrows showing the net force relative to the local gravitational force, $(F_{rad}+F_g)/|F_g|$. At the time shown in the simulation the 100 $M_\odot$ entire core has collapsed into the disk surrounding a 50 $M_\odot$ binary system.

2006; Kratter, Matzner, & Krumholz 2008), but these simulations were the first to demonstrate it numerically.

The first simulation of the collapse of a high-mass core including the effect of protostellar outflows Figure 2 (Cunningham, Klein, McKee & Krumholz 2009 in preparation) shows that the disk fragments into a binary system in the same manner as the case without outflow feeback. In this case the bipolar outflow carves a cavity of sufficiently low optical depth to beam radiation away from the incoming gas without forming a radiation pressure supported bubble. Including outflow effects, however, has a large influence on the star formation effiiency. In this case only 50% of the initial mass of the core has accreted onto the binary star system. The remainder of the gas has been ejected or entrained into the outflow.

6. Feedback Effects in Low Mass Star Formation

Forming stars emit a substantial amount of radiation into their natal environment with potentially considerable impact on gas temperatures and fragmentation (Boss et al. 2000; Whitehouse & Bate 2006). Nonetheless, previous simulations of low-mass star formation have typically neglected radiation feedback or used an approximate prescription to represent heating (e.g., Stamatellos et al. 2007; Banerjee & Pudritz 2007; Bonnell & Rice 2008). We have recently performed 3D radiation-hydrodynamic simulations to follow the evolution of stars forming in a $\sim 200 M_\odot$ clump including luminosity emitted on scales down to the stellar surface (Offner et al. 2009). Figure 3 shows the simulation column density, gas density, and gas temperature at one dynamical time. We compared simulations with and without radiative transfer and demonstrated that radiative feedback profoundly effects accretion, multiplicity, and mass by reducing the number of stars formed and the total rate at which gas turns into stars. We also showed that protostellar radiation is the dominant source of energy in the simulation, exceeding both viscous dissipation and compressional heating by one to four orders of magnitude, thus its inclusion is crucial in simulations modeling star formation. A low resolution simulation when not taking into account accretion luminosity predominantly emitted at the protostellar surface can significantly neglect a large component of the heating such as Bate 2009. In that simulation, with a minimum resolution of 0.05 AU and accretion luminosity emitted at 5 $R_{\odot}$, the luminosity is underestimated by a factor of 20, resulting in an underestimation of the temperature by $\approx$ 2–3. This can result in an overestimation of small scale fragmentation and a corresponding overproduction of Brown Dwarfs. Our simulations show that the large temperature range (10–50K) in the radiative transfer simulation has a profound effect on stellar mass distribution. Increased thermal support in protostellar disk acts to suppress disk instability and secondary fragmentation In the core. Our simulations with radiative transfer and radiative heating feedback yield star formation rates of 7% in good agreement with observed rates of 3–6% in contrast to simulations that use an equation of state that yield star formation rates $\sim$ 15%. Feedback from radiation also has a significant effect on initial stellar system multiplicity. We find that with radiative transfer included, the majority of stars formed are single or binary stars. If an equation of state is used instead, the majority of stars are formed in multiple systems of 2 or more stars due to continued disk fragmentation.

Unlike the radiative feedback from massive stars, low mass stars influence their surroundings within only 0.05 pc of the forming protostar. Thus radiative heating significantly affects fragmentation in the surrounding protostellar disk, but because the heating is local, there is no significant inhibition of turbulent fragmentation elsewhere in the core whereas the simulations with an equation of state suffer high rates of fragmentation.

7. Summary and Future Directions

For high mass star formation, we have shown 3-D high resolution AMR simulations with ORION achieve protostellar masses considerably above previous 2-D axisymmetric gray simulations. We have identified two new mechanisms that been shown to overcome the radiation pressure barrier to achieve high mass star formation and that gravitational instabilities in the protostellar disk result in a high mass binary system (Krumholz, Klein, McKee, Offner & Cunningham 2009). Our simulations demonstrate that 3-D Rayleigh-Taylor instabilities in radiation driven bubbles appear to be important in allowing accretion onto protostellar core and that protostellar outflows resulting in optically thin cavities promote the focusing of radiation and reduction of radiation pressure which subsequently enhances accretion. Thus radiation pressure cannot halt accretion and prevent the formation of high mass stars.

For low mass star formation we have demonstrated that Inclusion of radiative transfer has a profound effect on temperature distribution, accretion and final stellar masses. Heating by radiative transfer stabilizes protostellar disks

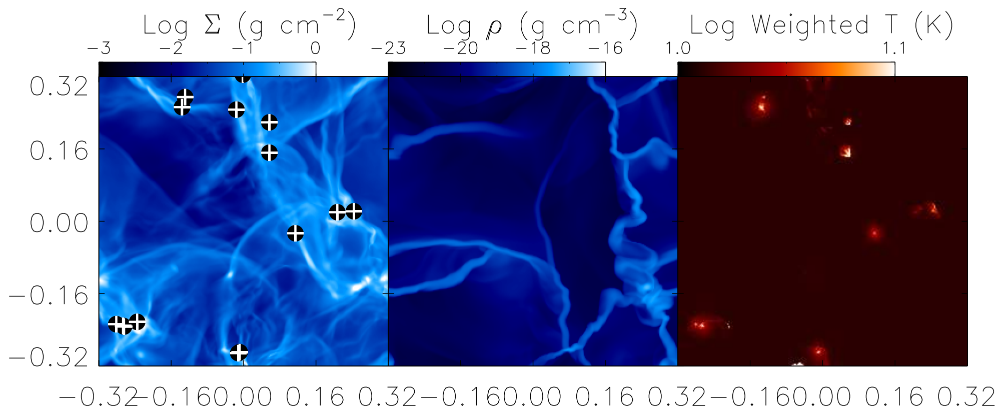

Figure 3. The left panel shows the gas column density with the protostars marked by crosses; the central panel shows a slice through the box gas density; the right panel shows the column of the gas temperature renormalized by the box length to give an effective temperature in degrees K. Taken from Offner et al. 2009

and suppresses small scale fragmentation. The vast majority of heating comes from protostellar radiation, not compression or viscous dissipation. For low mass star formation, the heating is local so there is no inhibition of turbulent fragmentation elsewhere.

For future directions it will be profitable to perform simulations with multi-frequency radiation hydrodynamics, inclusion of photionization and magnetic fields and eventual improvement over the flux limited diffusion approximation with a variable tensor factor approach or implementation of Sn transport.

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